

Re-weighting the evidence for a light Higgs boson in dileptonic W-boson decays

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We reconsider observables for discovering and measuring the mass of a Higgs boson via its dileptonic decays $h \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$. We define an observable generalizing the transverse mass that takes into account the fact that one of the intermediate W -bosons is likely to be on-shell. We compare this new variable with existing ones and argue that it gives a significant improvement for discovery in the region $m_h < 2m_W$.

The LHC has effectively put an upper bound on the mass of the Standard Model Higgs boson of around 140 GeV. The low mass region that remains is favoured by electroweak precision tests and theoretical bias (given the existing lower bound of 114 GeV coming from LEP), but is the most difficult to probe at the LHC, involving challenging final states with low signal cross section and large backgrounds. One final state that is relevant right now comes from Higgs decays to W bosons, which in turn decay leptonically, $W \rightarrow \ell\nu$. Here we propose a new observable to improve the discrimination between signal from background in this channel.

To motivate the discussion, let us first consider the transverse mass observable [1], originally used in the discovery of the W -boson [2]. One way to define the transverse mass is as the observable that gives the greatest lower bound on the mass of the W -boson, given the constraints that follow from conservation of energy-momentum and from the assumption that particles are on-shell [3]. The utility of this definition, which seems rather cumbersome for something as simple as W -boson decays, is that it allows a generalization to any decay process involving missing energy, once one makes a hypothesis for the decay topology. The resulting variable is the natural variable for that topology, in the sense that it encodes all of the information available from kinematic considerations alone.¹ It results in a distribution in which signal events pile up below the mass of the parent resonance, facilitating both discovery of that resonance and measurement of its mass.

In [13] (see also [15, 16]), this logic was used to define a new observable for measuring the mass of a Higgs boson that decays with significant branching fraction to a pair of charged leptons (which we refer to henceforth as simply leptons) and a pair of neutrinos. The resulting variable

has a simple algebraic form, given by

$$(m_T^{\text{true}})^2 = m_{\ell\ell}^2 + 2 \left(\sqrt{(m_{\ell\ell}^2 + \vec{p}_{\ell\ell T}^2) \vec{p}_T^2} - \vec{p}_T \cdot \vec{p}_{\ell\ell T} \right), \quad (1)$$

where $\vec{p}_{\ell\ell T}$ and $m_{\ell\ell}$ are the transverse momentum and invariant mass of the lepton pair and \vec{p}_T is the measured missing transverse momentum in the event. It was shown in [13] that this variable gave an improvement over other variables, both for discovery and mass measurement. The variable was subsequently adopted by the ATLAS and CMS collaborations, who found a further advantage in the form of a reduced correlation with other variables used for discriminating signal and backgrounds [17].

Though the variable defined in [13] uses all the kinematic information in the *final* state, there remains the possibility that advances can be made using the internal kinematic structure of the Higgs decay. Indeed, one or both of the W -bosons produced by the Higgs decay will be almost on-shell [18], at least for a Higgs mass in the region where there is significant branching fraction to $WW^{(*)}$. We will demonstrate that (1) is not, therefore, the optimal observable.

Similar ideas were recently applied in [14] to the decay of a light Higgs into $\tau\tau$. In that case, both of the τ mesons will be on-shell in the interesting region of Higgs masses, and it was shown that the variable, m_T^{bound} , that takes this into account in its definition significantly outperforms the variable m_T^{true} defined in Ref. [13].

Let us then reconsider the decay $h \rightarrow WW^{(*)}$ and the dominant background – continuum WW production. We define a new variable, m_T^* , defined to give the greatest lower bound on the mass of the Higgs, subject to the assumption that one or other of the two W -bosons is produced on-shell. Explicitly, denoting the 4-momenta of the charged leptons and neutrinos by $p_{1,2}^\mu$ and $q_{1,2}^\mu$, respectively, we minimize $(p_1^\mu + p_2^\mu + q_1^\mu + q_2^\mu)^2$ subject to the constraints that either $(p_1^\mu + q_1^\mu)^2 = m_W^2$ or $(p_2^\mu + q_2^\mu)^2 = m_W^2$, and $\vec{q}_{1T} + \vec{q}_{2T} = \vec{p}_T$.²

¹ In the case of pair decays in supersymmetric theories, this definition picks out [3–5] the variable m_{T2} [6, 7]; it may also be applied in situations with combinatorial ambiguities [8], in the presence of initial state radiation [9], or in situations where one may assume that invisible particles are collinear with visible particles [10]. Applications to Higgs boson searches include [11–14].

² We have not been able to obtain a simple algebraic form for m_T^* ; instead we evaluate it via an algorithm implemented on a

It is a simple matter to show that $m_T^* \rightarrow m_T^{\text{true}}$ in the limit that $m_W \rightarrow 0$, so that there is no advantage to be gained in using m_T^* in place of m_T^{true} if m_h (or \hat{s} for background events) is large compared to m_W . (Proof: Assignments of the unknown neutrinos' momenta that yield a value of m_T^{true} for the invariant mass of the WW system correspond to (i) vanishing invariant mass of the di-neutrino system and (ii) vanishing relative rapidity between the di-lepton and di-neutrino systems. One of these assignments also yields (iii) vanishing invariant mass for one lepton-neutrino pair and thus satisfies the extra constraint that defines m_T^* in the limit $m_W = 0$. To wit, (i) and (iii) may be satisfied trivially by assigning vanishing three-momentum to one of the neutrinos; the three-momentum of the other neutrino is then fixed uniquely by the measured \vec{p}_T , which fixes the transverse components, and by (ii), which fixes the longitudinal component.³) Away from the limit of small m_W , and in particular for $m_h < 2m_W$, the extra constraint requiring one of the W -bosons to be on-shell implies that $m_T^* > m_T^{\text{true}}$. Moreover, since $m_T^{\text{true}} < m_T^* \leq m_h$ for signal events, we might hope for an increased number of signal events, relative to background, in a region below m_h , increasing our ability to discriminate between the background-only and signal-plus-background hypotheses in an analysis based on counting events in such a region.

We now compare the performance of the two variables m_T^{true} and m_T^* , using a simulation of LHC events corresponding to 10 fb^{-1} of integrated luminosity. We use the HERWIG 6.505 [20, 21] Monte Carlo generator, with LHC beam conditions ($\sqrt{s} = 7 \text{ TeV}$). Our version of the generator includes the fix to the $h \rightarrow WW^{(*)}$ spin correlations described in [22].

We generate unweighted events for Standard Model Higgs boson production ($gg \rightarrow h$) and for the dominant background, $q\bar{q} \rightarrow WW$. The detector resolution is simulated by smearing the magnitude of the missing momentum vector with a Gaussian resolution function of width $\sigma_{p_T}/p_T = 0.4 \text{ GeV}^{1/2}/\sqrt{\Sigma}$ where Σ is the sum of the $|\vec{p}_T|$ of all visible fiducial particles.

Selection cuts are applied based on [23, 24], requiring:

- Exactly two leptons $\ell \in \{e, \mu\}$ with $p_T > 15 \text{ GeV}$ and $|\eta| < 2.5$
- Missing transverse momentum, $\cancel{p}_T > 30 \text{ GeV}$
- $12 \text{ GeV} < m_{\ell\ell} < 300 \text{ GeV}$

standard personal computer. The relevant code is available online [19]. Unlike the variable m_T^{bound} [14], one may show that m_T^* is well-defined for any input momentum configuration.

³ Similar arguments show that the m_T^{bound} variable does not coincide with m_T^{true} in the same limit: to enforce the intermediate mass-shell constraints, both neutrinos would have to be assigned vanishing three-momentum, which would be incompatible with the observed non-vanishing \vec{p}_T .

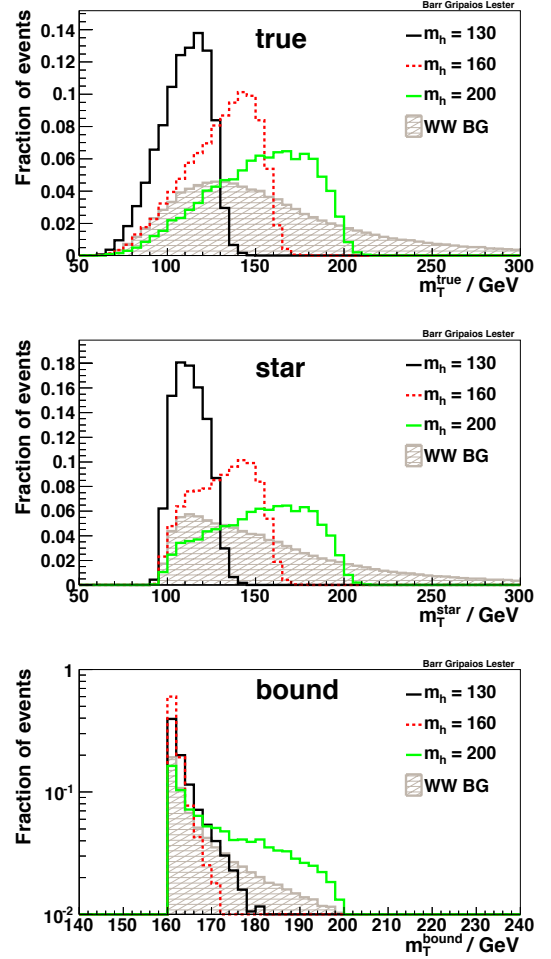


FIG. 1: Simulation of $h \rightarrow WW$ signal (for $m_h \in \{130, 160, 200\} \text{ GeV}$) for the variables m_T^{true} (above), m_T^* (middle) and m_T^{bound} (below). The shading gives the shape of the dominant WW background. It should be noted that a logarithmic y -axis scale (and displaced x -axis) has been used when plotting m_T^{bound} .

- No jet with $p_T > 20 \text{ GeV}$
- $Z \rightarrow \tau\tau$ rejection: the event was rejected if $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$ and $0 < x_i < 1$ for both $i \in \{1, 2\}$ ⁴
- Relative azimuth $\Delta\phi_{\ell\ell} < \Delta\phi_{\ell\ell}^{\text{max}}$
- Transverse momentum of the W pair system, $p_{TWW} > 30 \text{ GeV}$
- The appropriate transverse mass (m_T^* or m_T^{true}) must satisfy $0.75 \times m_h < m_T < m_h$.

⁴ The variable x_i is the momentum fraction of the i th tau carried by its daughter lepton and $m_{\tau\tau}$ is the di-tau invariant mass. They are calculated using the approximation that each τ was collinear with its daughter lepton.

The value chosen for $\Delta\phi_{\ell\ell}^{\max}$ is either 1.3 or 1.8, where we use the value for which the larger discovery potential is expected.

In Fig. 1 we show sample distributions of the variables m_T^{true} and m_T^* for both the signal (for various m_h) and WW background before any cuts are applied. As expected, the signal distributions for both variables are bounded above by m_h (the upper endpoint of the distribution in the absence of resolution and finite width effects). The W mass-shell constraint means that, by construction, m_T^* is larger than m_W . The effect of the additional constraint is that both signal and background events having $m_T^{\text{true}} < m_W$ must migrate to values larger than m_W , while events with m_T^{true} significantly larger than m_W are little changed (i.e. have $m_T^* \approx m_T^{\text{true}}$), in accordance with the arguments given above. We also show, for comparison, the distribution of the variable m_T^{bound} . This need not be bounded above by m_h if the assumption that both W -bosons are on-shell is invalid.

In Fig. 2 we compare the Higgs discovery potential, as a function of m_h , using only m_T^{true} (dotted, shaded) or m_T^* (solid, open), as measured by the difference in log likelihood between models with or without a Higgs boson. In this figure we see the key result of this note: the Higgs boson discovery potential is improved in the region $m_h < 2m_W$ and is unchanged elsewhere. This gives a strong indication that m_T^* is to be preferred to m_T^{true} for Higgs discovery purposes. This improvement may, of course, be mitigated by an increased correlation of the new variable with other variables used in the analysis; we leave this for further investigation. However, we remark that our cuts were not optimised for m_T^* . Optimisation for m_T^* might lead to improvements in discovery potential for $m_h < 2m_W$ which are greater than those we have shown already. As expected, for Higgs boson masses above $2m_W$ we have $m_T^* \simeq m_T^{\text{true}}$, and so both variables are equally successful there. This begs the question: “Are there better ways of searching for Higgs bosons in this mass range?” For these larger masses one might be prepared to make the hypothesis that *both* W -bosons are produced on shell, in which case one could employ the variable m_T^{bound} proposed in [14]. Further simulations [25] suggest that using this variable *does* lead to an improvement over m_T^{true} and m_T^* for $m_h > 2m_W$ so it may be possible to gain improved sensitivity for both large and small Higgs boson masses.

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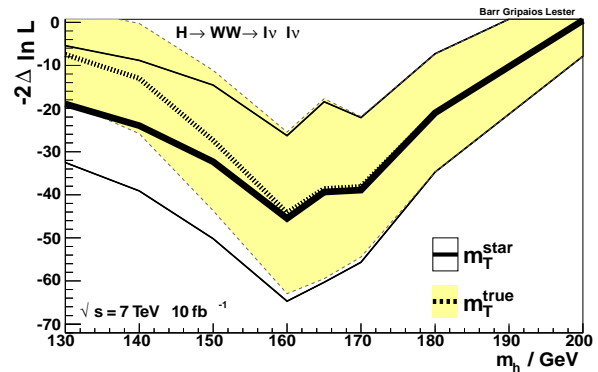


FIG. 2: Higgs boson discovery potential as a function of m_h , using only m_T^{true} (dotted, shaded) or m_T^* (solid, open). The center of each band indicates the difference in log likelihood between models with and without a Higgs boson contribution. Lower values correspond to better discovery potential. The half-width of the each band gives the root-mean-squared over 50 trial samples. The integrated luminosity simulated is 10 fb^{-1} .

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Erratum: Re-weighting the evidence for a light Higgs boson in dileptonic W-boson decays [Phys. Rev. Lett. 108 041803 (2012)]

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The plot in the published Fig. 2 of [1] is incorrect, due to an error in the calculation of the likelihood function. As a result, our simulations suggest that m_T^* provides discrimination very similar to (but no better than) m_T^{true} for the specific Higgs boson decay described and equal discovery potential to m_T^{true} , when the event selection cuts used by the ATLAS Collaboration in [2, 3] are applied. The correct plot is shown in Fig. 1. The generic arguments given in the rest of the Letter are unaffected.

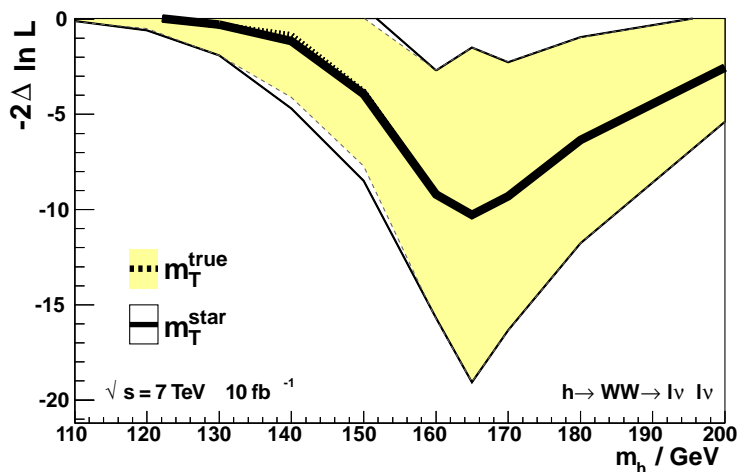


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